

CFD Simulations for Arc-Jet Panel Testing Capability Development Using Semi-Elliptical Nozzles

Tahir Gökçen,* John A. Balboni, and G. Joseph Hartman††**

NASA Ames Research Center, Moffett Field, CA 94035

* AMA, Inc.

** Thermo-Physics Facilities Branch

†† Jacobs Technology, Inc.

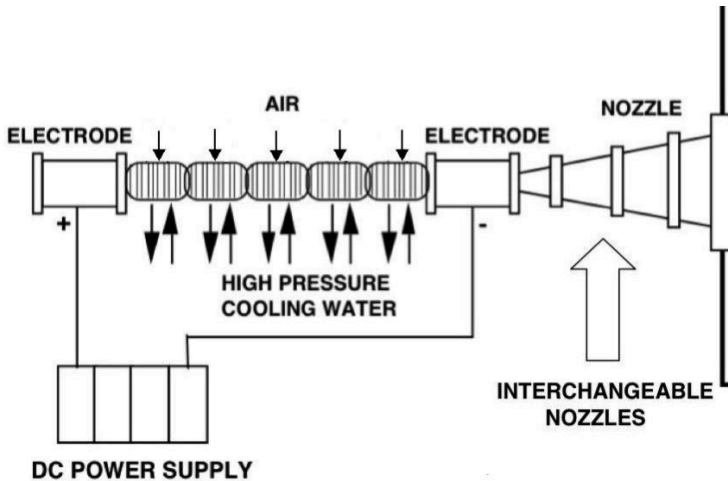
This work is performed at NASA ARC Entry Systems and Technology Division

AIAA Paper 2016-3518

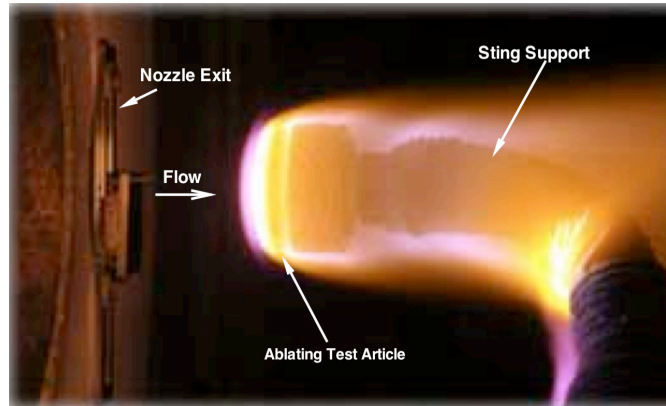
AIAA AVIATION 2016 Conferences: Session GT-06

June 13-17, 2016, Washington, DC

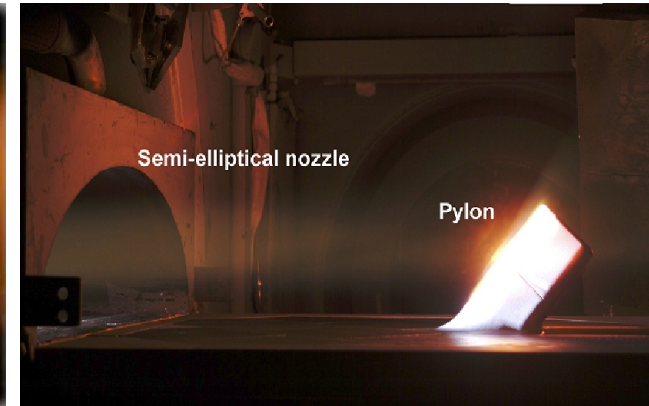
Introduction to Arc-Jets and Testing



Arc-heater/nozzle sketch



Stagnation coupon



IHF panel/pylon test



IHF wedge test



PTF panel test

- Arc-jets provide the primary means to test the performance of various types of thermal protection systems (TPS) in an aerothermodynamic heating environment
- Set of conical nozzles or semi-elliptical nozzles
- Free jet test configuration with stagnation coupon or wedge models
- Semi-free jet test configuration with panel test articles

NASA Ames Arc-Jet Facilities with Semi-Elliptical Nozzles



IHF water-cooled calibration plate



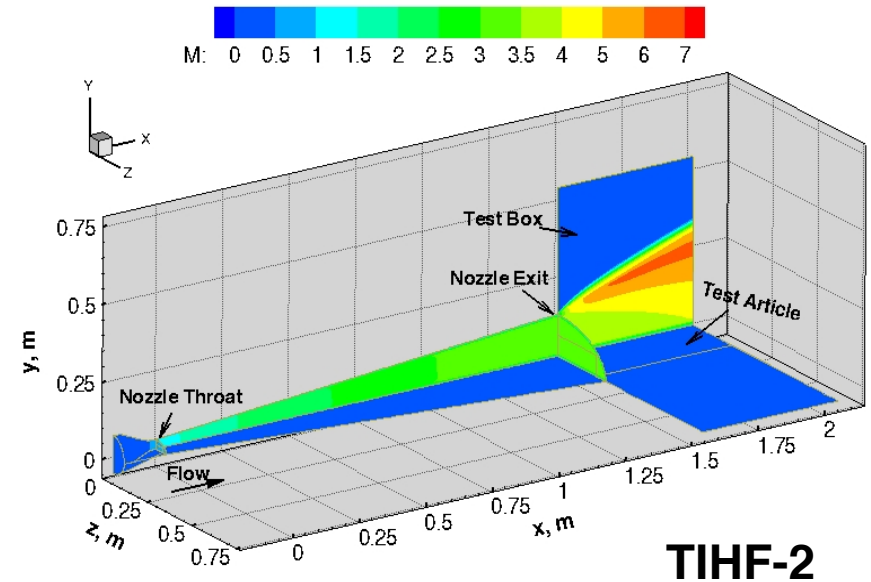
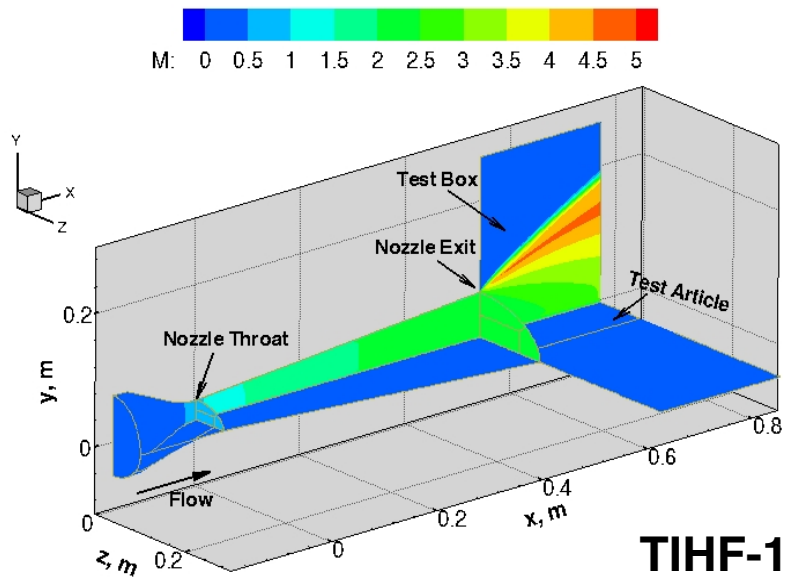
PTF panel test

- ARC has two panel test facilities with semi-elliptical nozzles: 20-MW Panel Test Facility (PTF) and 60-MW Interaction Heating Facility (IHF)
- Semi-free jet test configuration: test articles, usually flat panels, are mounted flush to the bottom surface of the nozzle in a supersonic jet at the nozzle exit
- This test configuration provides two important advantages over alternative testing using inclined wedge models in conical nozzles: (1) thicker boundary layers over the panel test articles, and (2) the ability to test much larger panel test articles

Objectives and Scope

- Truncated IHF semi-elliptical nozzles are proposed to provide panel testing capability for Orion program under LEAF-Lite project
 - IHF SE nozzle is constructed for testing of relatively large-scale panels (61 cm x 61 cm or 24" x 24") at conditions of the Space Shuttle Orbiter vehicle Earth entry (5-25 W/cm²)
 - NASA is interested in panel testing capabilities at higher heating levels
 - Split the IHF SE nozzle at the existing junctions to create two new "truncated" (shorter) nozzles
 - Option 1 (TIHF-1): the first expansion at $x = 0.537$ m (21.129")
 - Option 2 (TIHF-2): the second expansion at $x = 1.506$ m (59.3")
- CFD simulations are performed to provide estimates of the achievable surface conditions and useful test area
 - Facility max condition
 - Two plate deflections: 0° and the max angle (4° for TIHF-1 and 6° for TIHF-2)
 - Estimates of surface pressure, cold-wall heat flux, and surface shear for panel test articles, the boundary layer thickness, and edge Mach number
 - Estimates of the useful panel test area (subjectively defined as the test area in which gradients of test article surface quantities are acceptable for evaluation of TPS performance)

Computational Approach



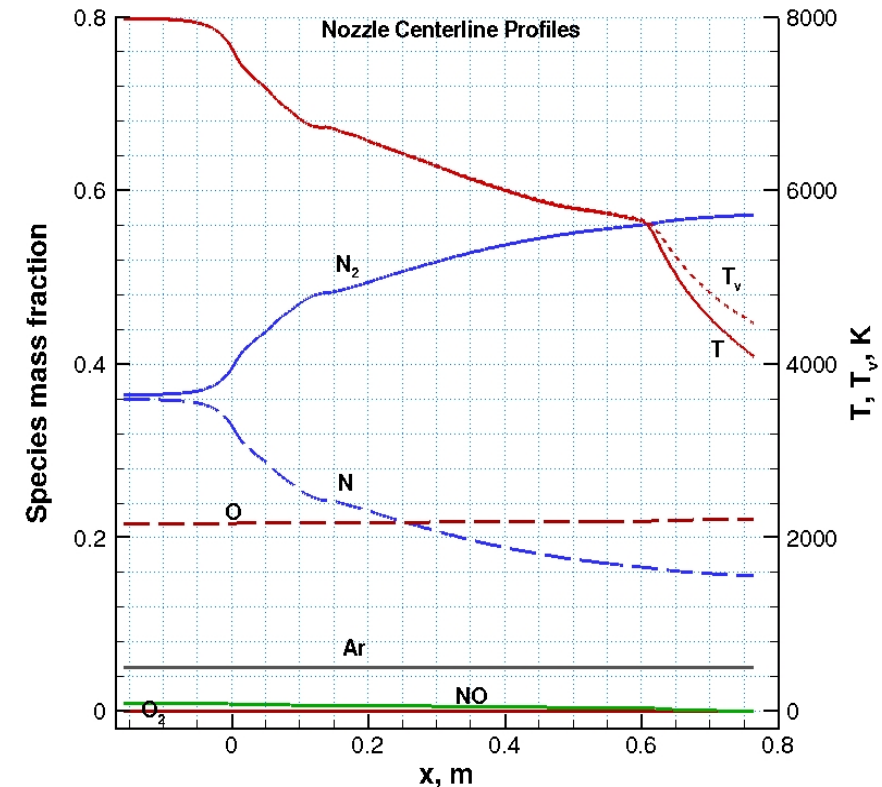
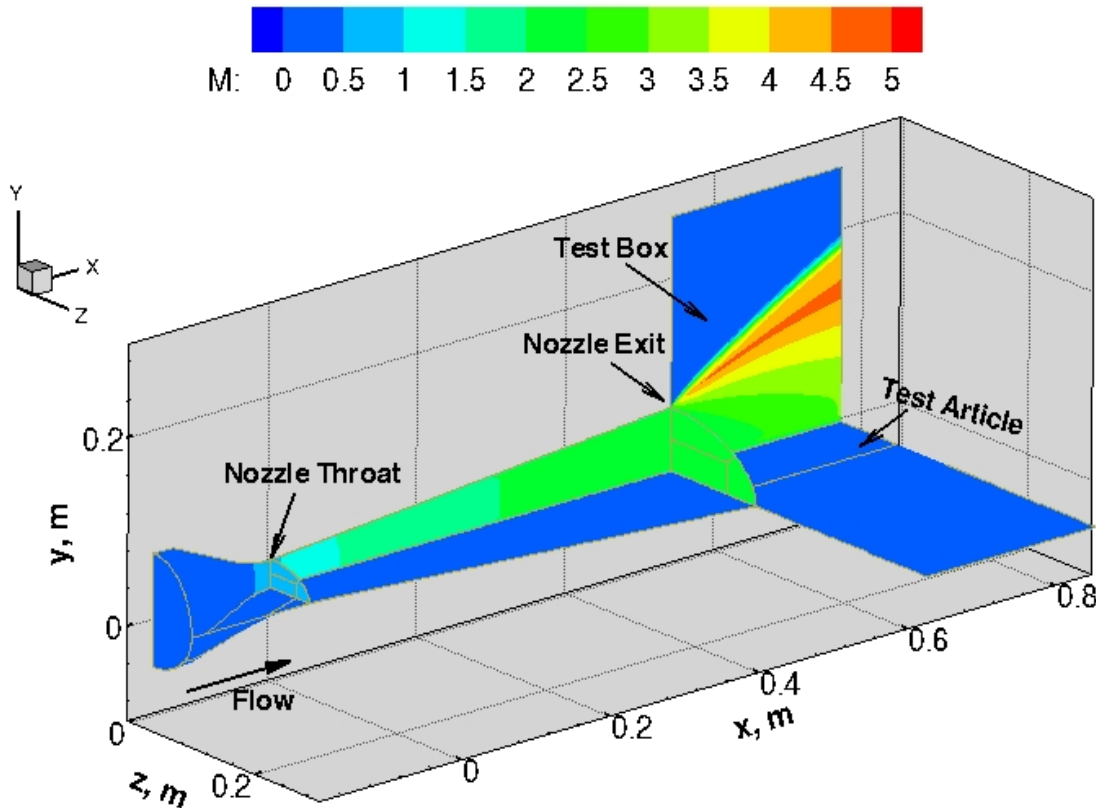
- CFD analysis includes simulations of nonequilibrium flow in the arc-jet facility (nozzle, test box, over the panel test article)
- Prescribe flow profiles at the nozzle inlet with chemical equilibrium composition
- 3-D Navier-Stokes equations with nonequilibrium processes
- Thermochemical model for arc-jet flow
 - Six chemical species: N_2 , O_2 , NO , N , O , Ar
 - Two-temperature model (Park): T -translational-rotational, T_v -vibrational-electronic
- Data-Parallel Line Relaxation Method - DPLR Code

Presentation of Computed Results

- Simulation results for TIHF-1 and TIHF-2 semi-elliptical nozzle options at one facility condition
 - $p_o = 900$ kPa, $h_o = 26$ MJ/kg, 5% Ar in air
 - Approximately the maximum condition achievable in the IHF (surface pressure and heat flux)
 - THIF-1, zero and 4° plate deflections
 - THIF-2, zero and 6° plate deflections
- Effects of a non-uniform enthalpy profile at the inlet on predicted test plate surface quantities are presented in the paper
 - Based on available IHF facility data and surveys in conical nozzles, the flow non-uniformity at the maximum facility condition is expected to be minimal
 - $p_o = 900$ kPa, $h_{ob} = 26$ MJ/kg, $h_{ocl} = 29.5$ MJ/kg, parabolic enthalpy profile, 5% Ar in air
 - TIHF-1 and TIHF-2 results at zero plate deflection are in the paper

Computed Mach Number Contours and Centerline Profiles

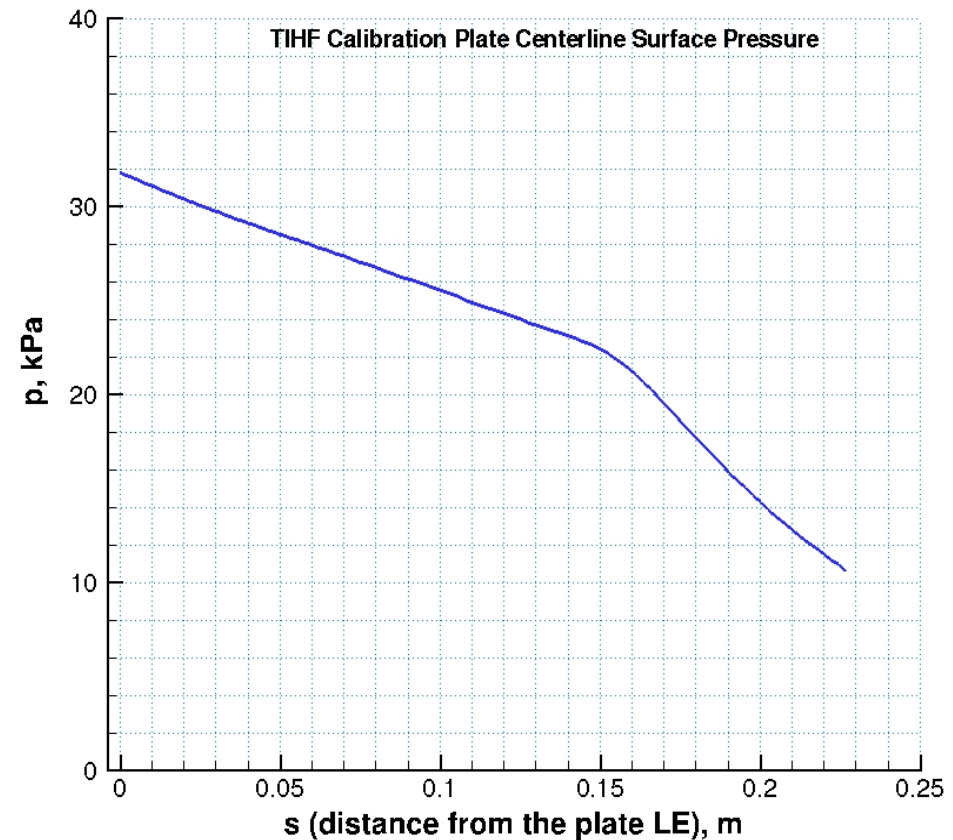
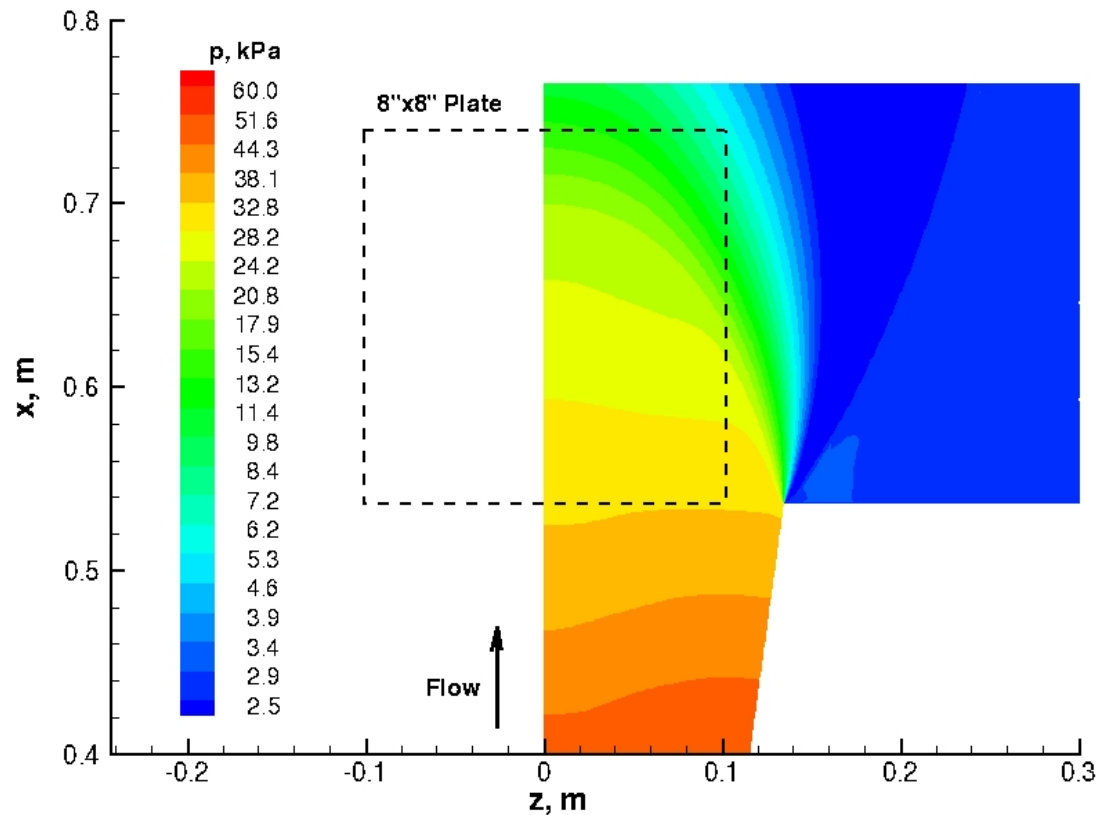
TIHF-1 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 0° plate deflection



- TIHF-1 (or IHF) semi-elliptical nozzle: the converging section starts with a circular shape and transitions into a semi-elliptical shape at the throat, and the diverging section expands conically from the throat to the test section, preserving its semi-elliptical shape
- Flow is in chemical and vibrational nonequilibrium
- Oxygen remains fully dissociated except in the boundary layer (and shear layer)
- Nitrogen is partially dissociated
- Mach number at the nozzle exit: 2.37

Computed Surface Pressure Contours and Centerline Profiles

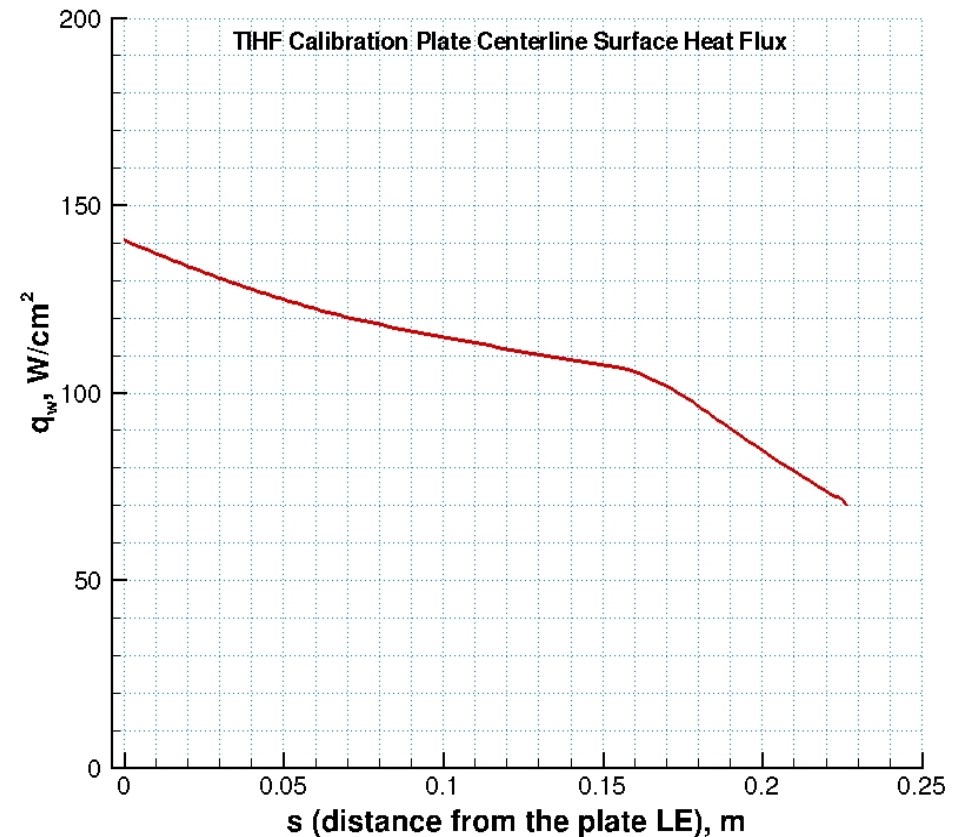
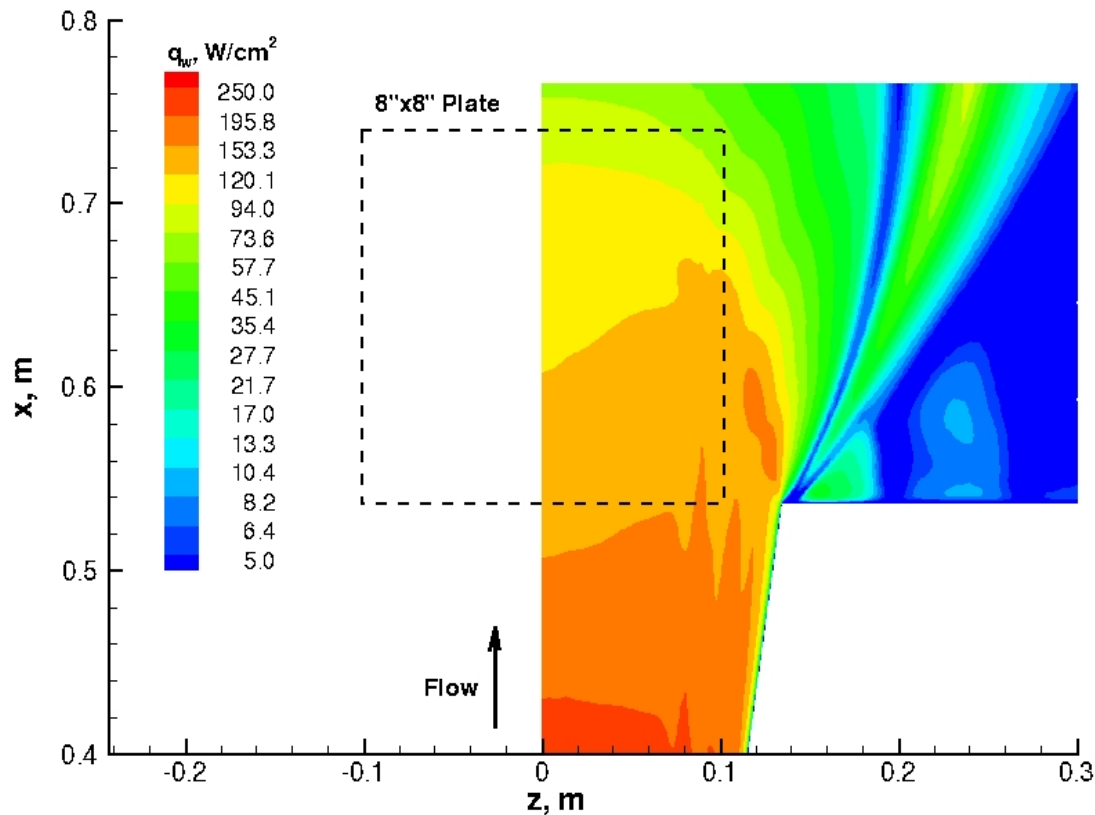
TIHF-1 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 0° plate deflection



- Top view shows surface pressure distribution over a 8"x8" panel test article
- Surface pressure range along the plate centerline: 31.8–13.8 kPa

Computed Surface Heat Flux Contours and Centerline Profiles

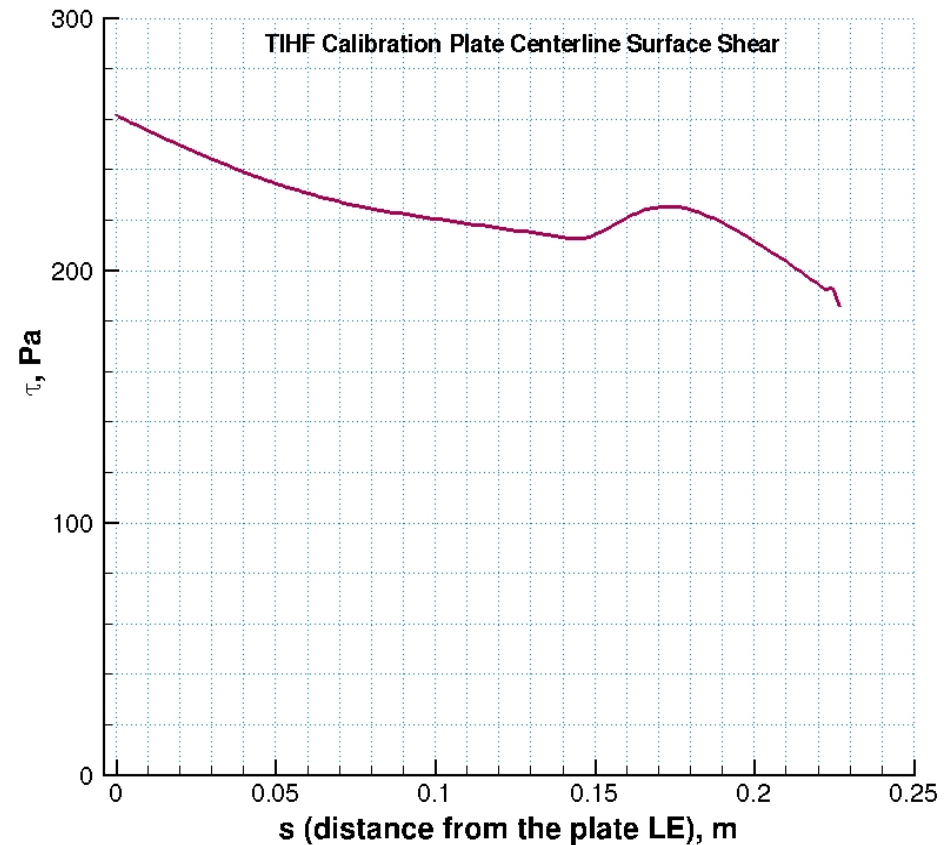
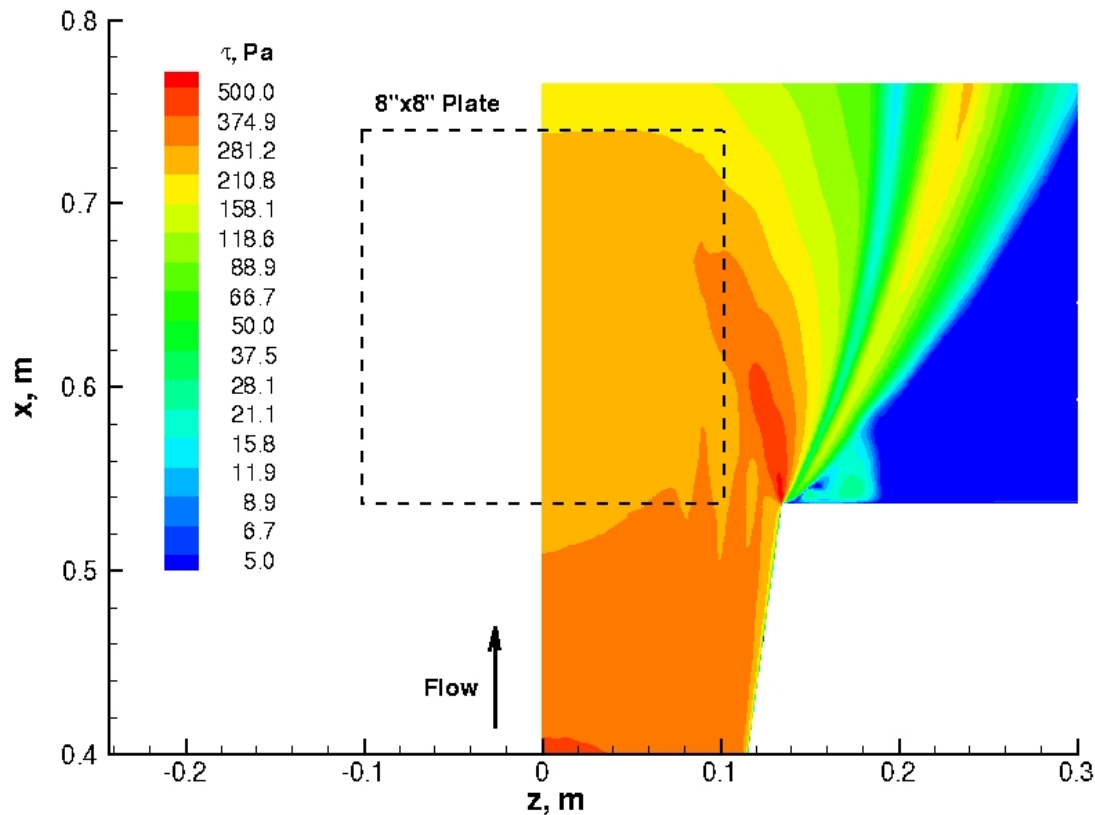
TIHF-1 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 0° plate deflection



- Top view shows surface heat flux distribution over a 8''x8'' panel test article
- CWFC heat flux range along the plate centerline: 141–83 W/cm^2

Computed Surface Shear Contours and Centerline Profiles

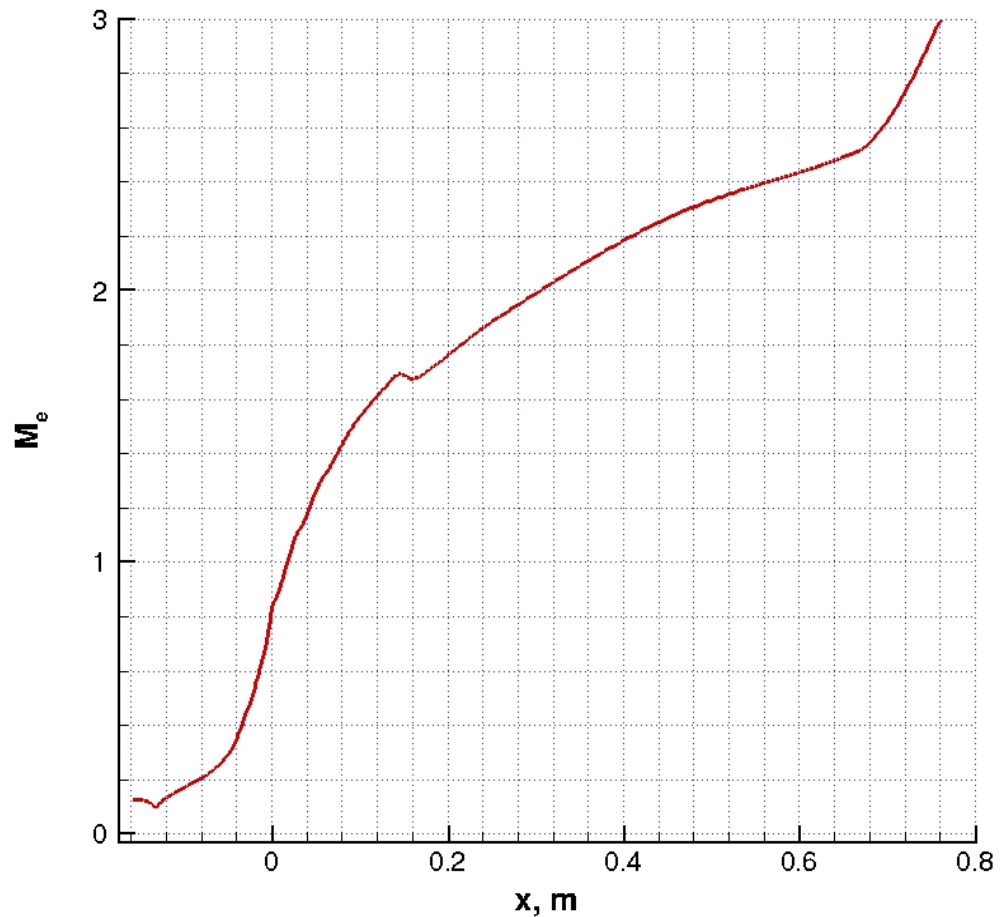
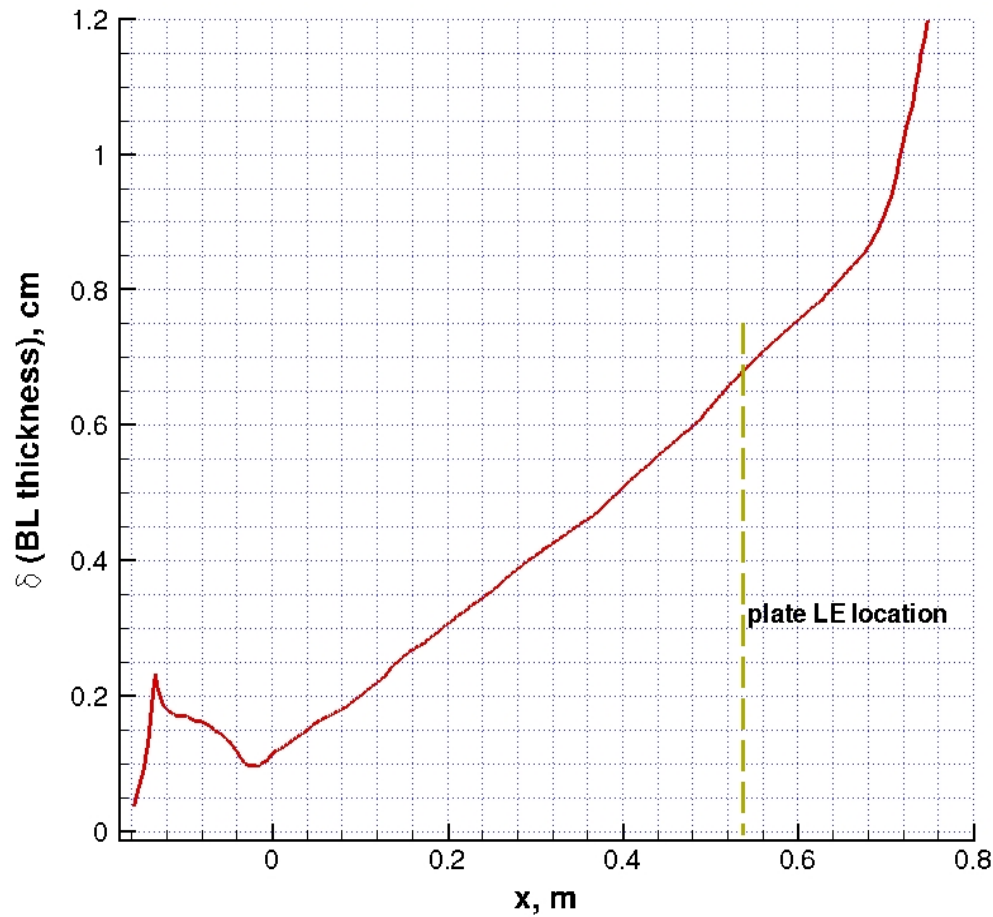
TIHF-1 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 0° plate deflection



- Top view shows surface shear distribution over a 8"x8" panel test article
- Surface shear range along the plate centerline: 262–210 Pa

Computed Boundary Layer Thickness and Edge Mach Number

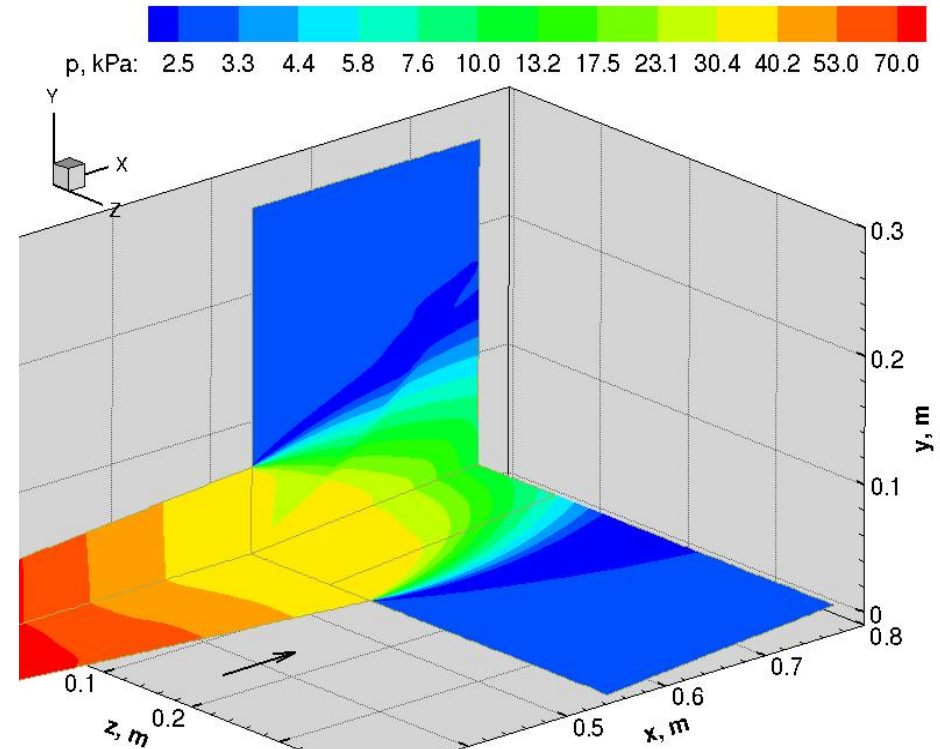
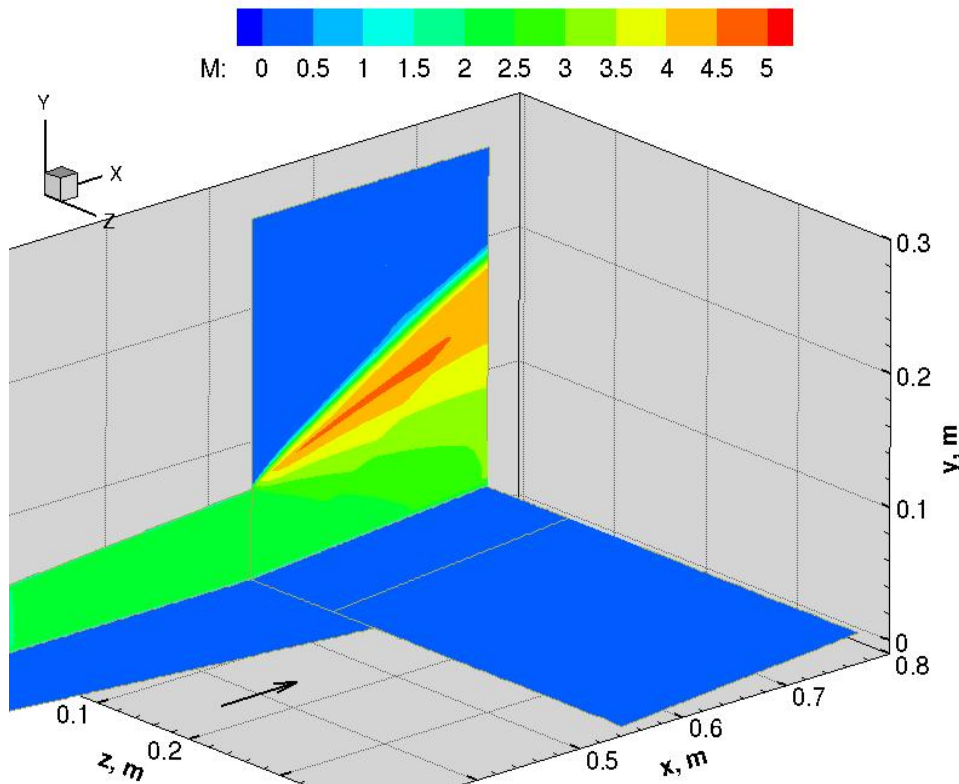
TIHF-1 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 0° plate deflection



- BLE is determined as the location of 99.5% freestream total enthalpy

Computed Flowfield Contours: Expansion Waves and Flow Interaction

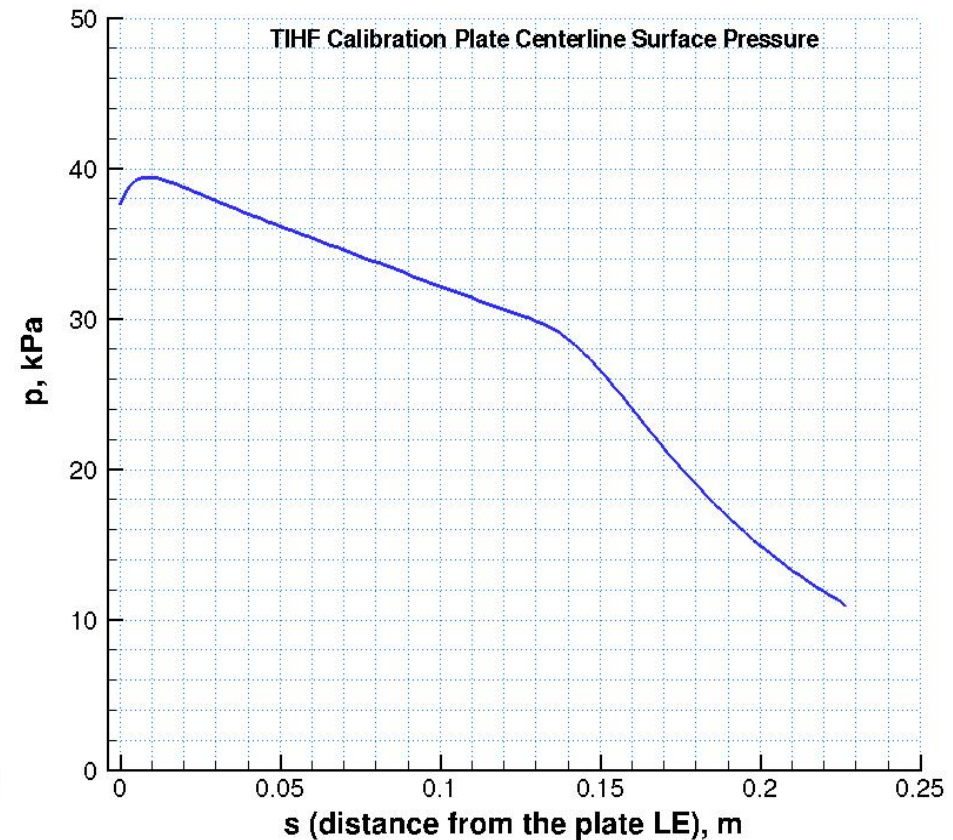
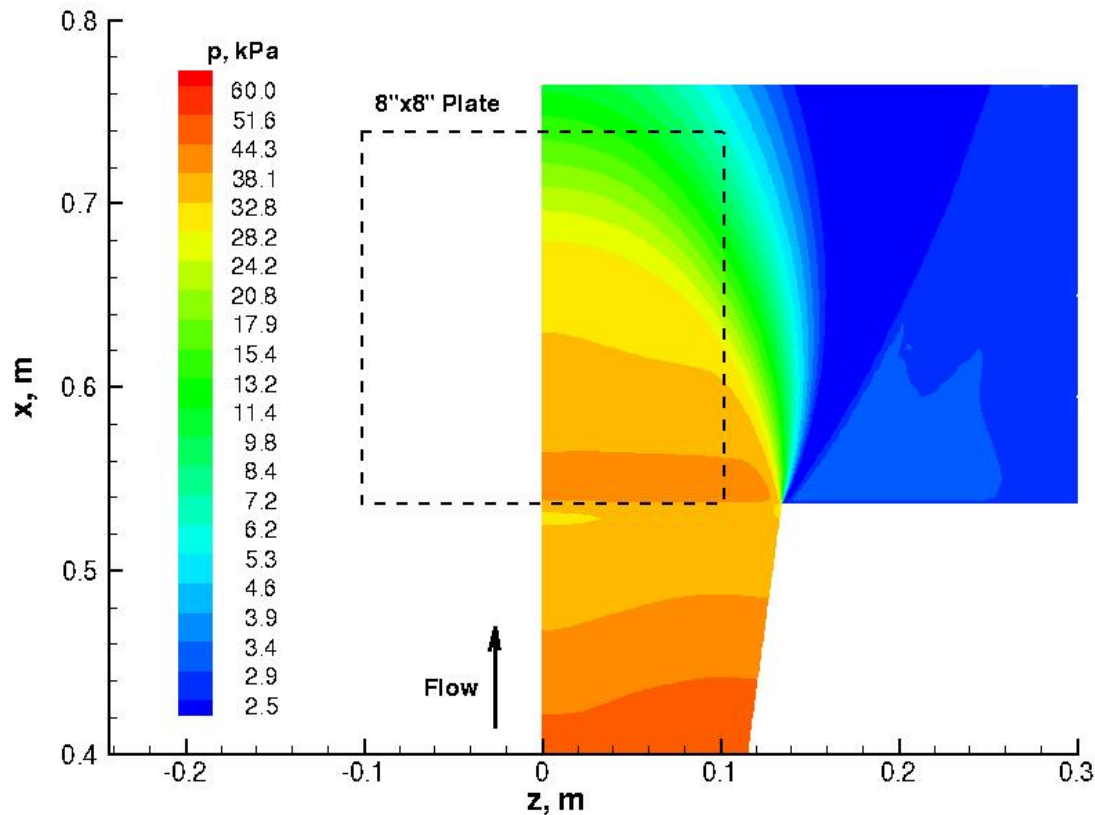
TIHF-1 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 4° plate deflection



- Mach number and pressure contours show the on-coming supersonic flow, expansion waves emanating from the corner of the nozzle exit, and their interaction over the deflected panel test article
- This flow interaction, with the exit Mach number and plate deflection angle being the most important parameters, ultimately determines the useful test area in this test configuration

Computed Surface Pressure Contours and Centerline Profiles

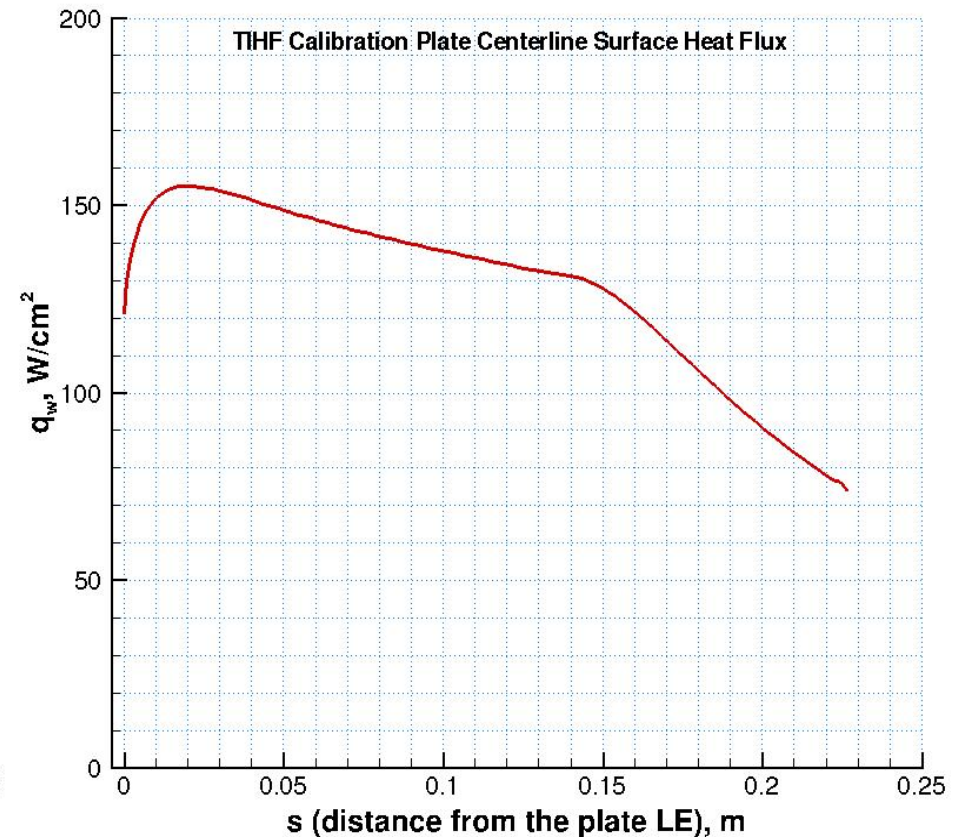
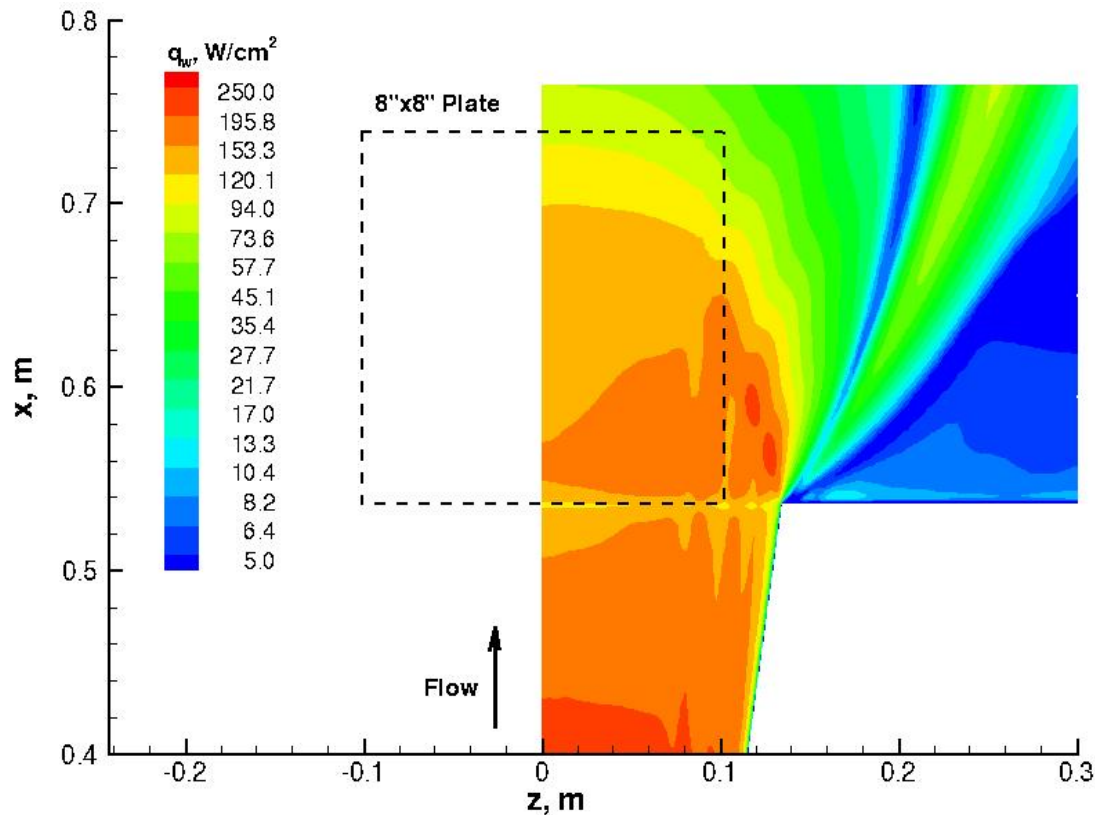
TIHF-1 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 4° plate deflection



- Top view shows surface pressure distribution over a 8"x8" panel test article
- Surface pressure range along the plate centerline: 39.4–14.5 kPa

Computed Surface Heat Flux Contours and Centerline Profiles

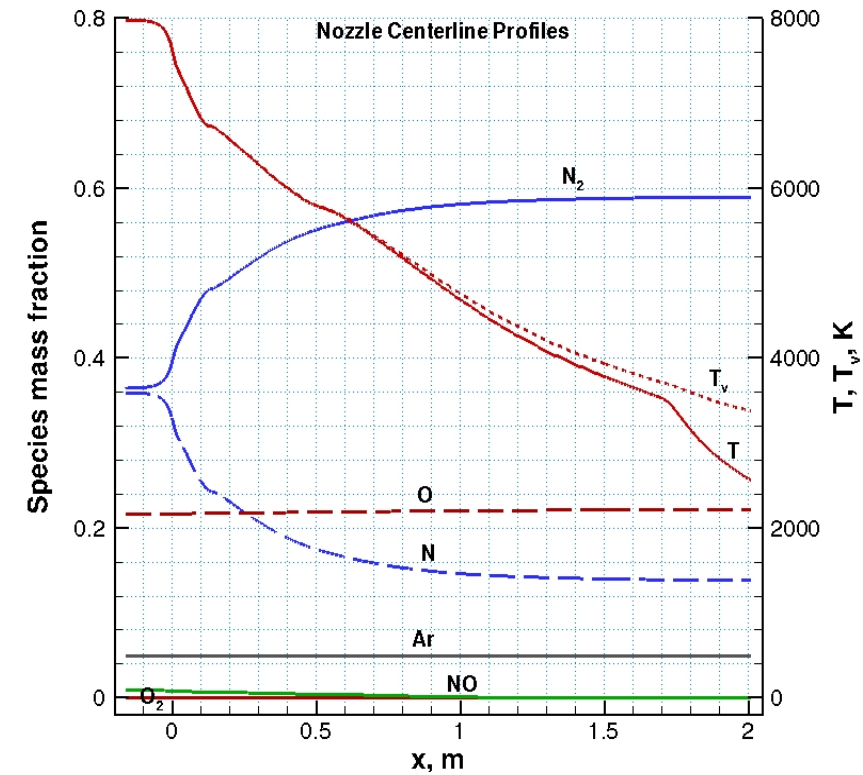
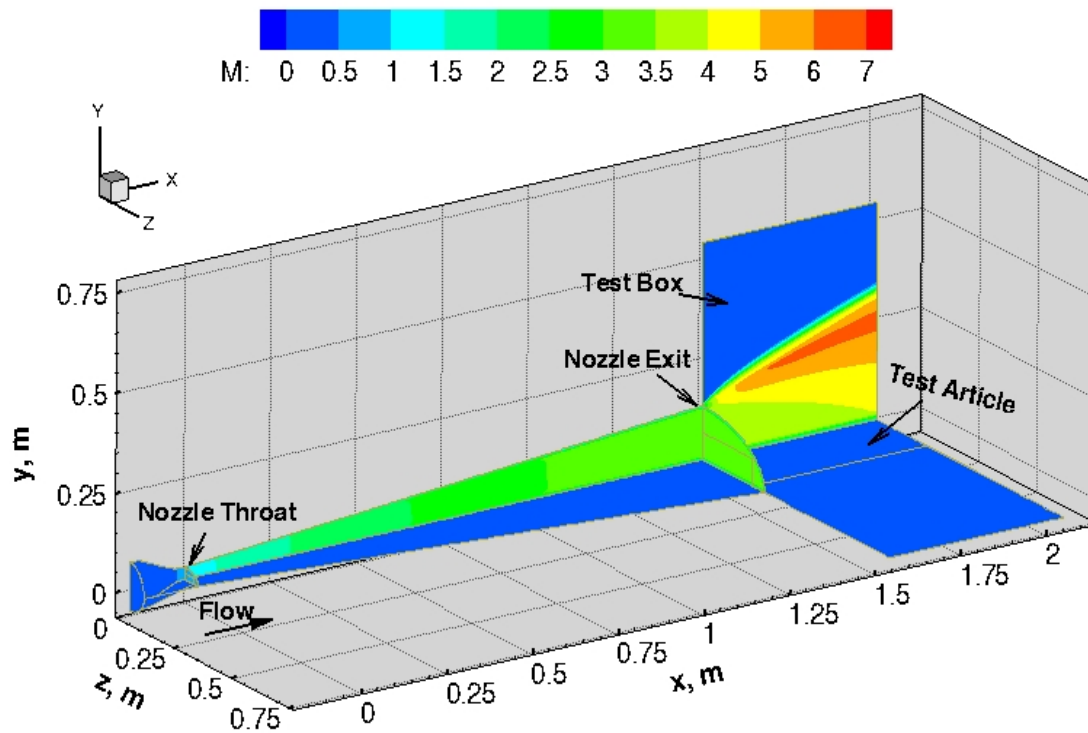
TIHF-1 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 4° plate deflection



- Top view shows surface heat flux distribution over a 8"x8" panel test article
- CWFC heat flux range along the plate centerline: 154–89 W/cm^2

Computed Mach Number Contours and Centerline Profiles

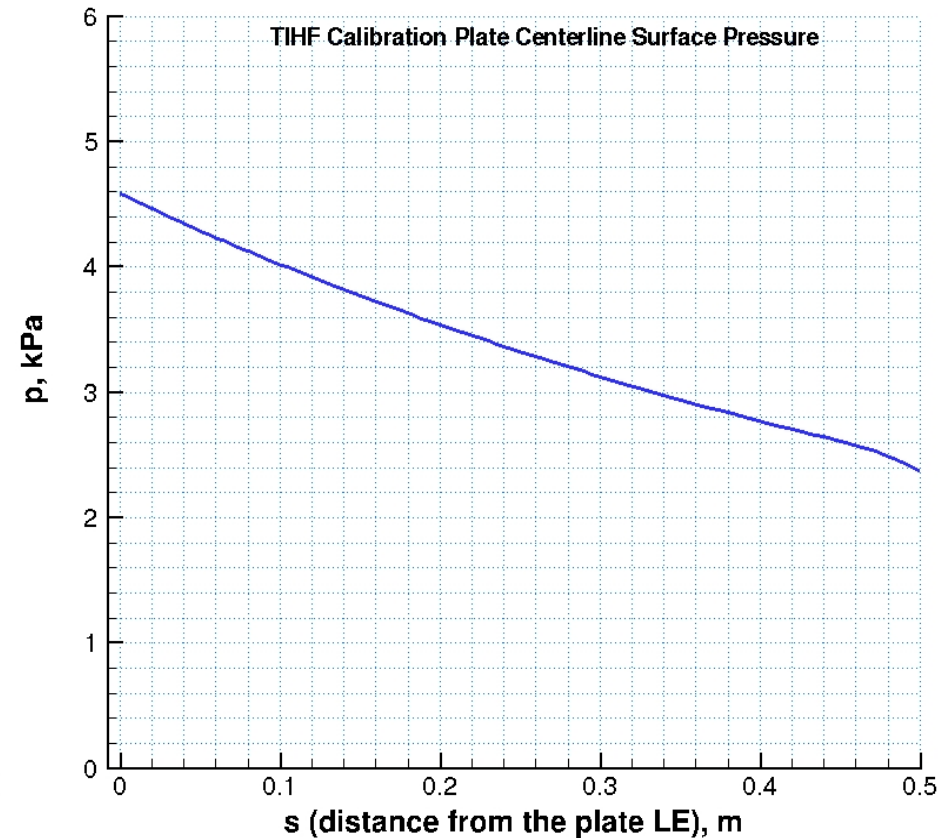
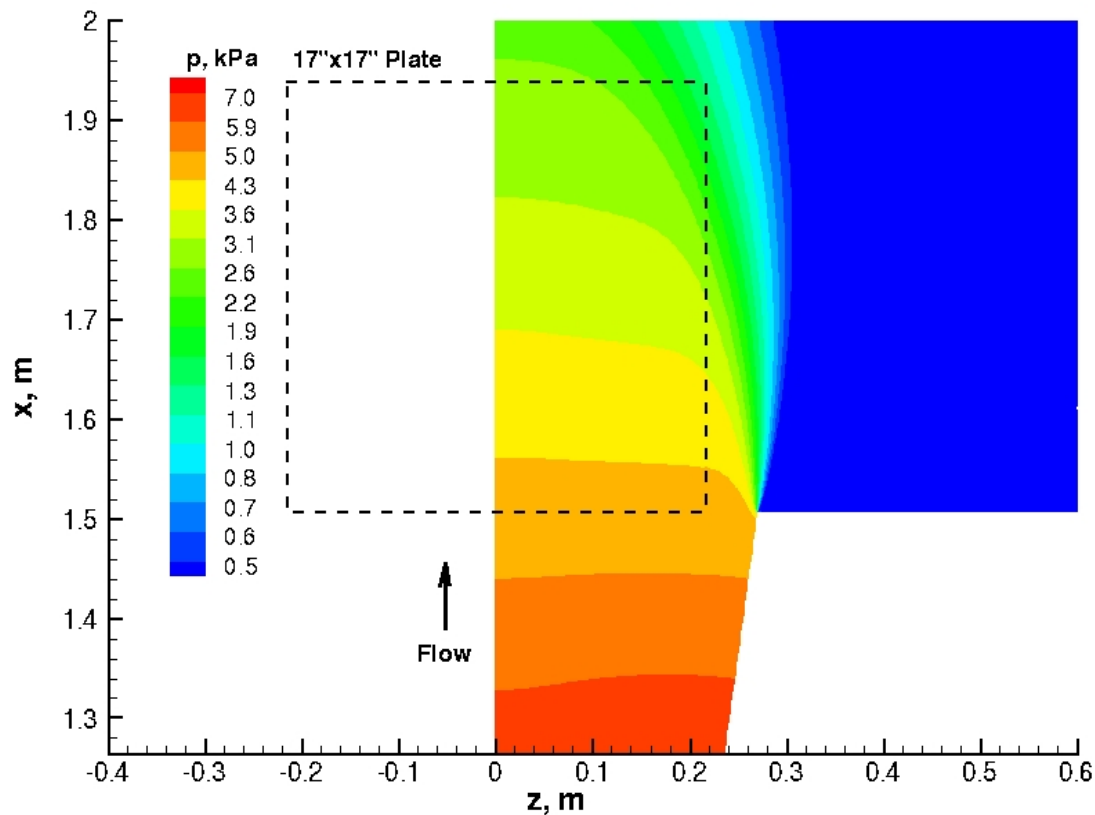
TIHF-2 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 0° plate deflection



- Flow is in chemical and vibrational nonequilibrium
- Oxygen remains fully dissociated except in the boundary layer (and shear layer)
- Nitrogen is partially dissociated
- Mach number at the nozzle exit: 3.47

Computed Surface Pressure Contours and Centerline Profiles

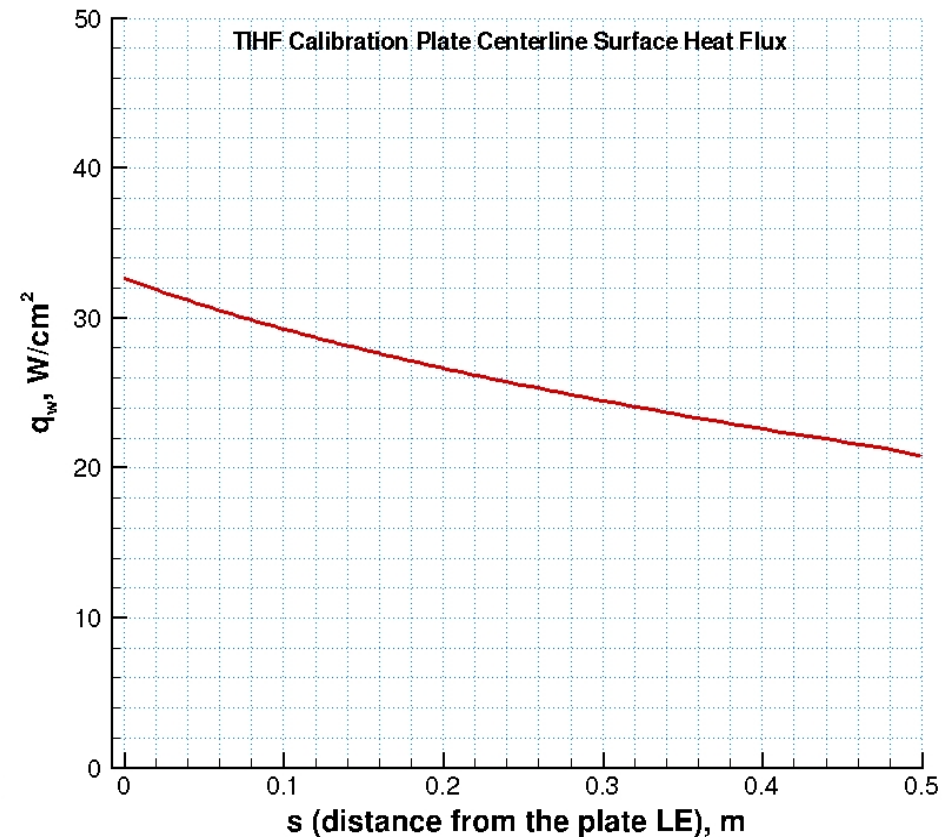
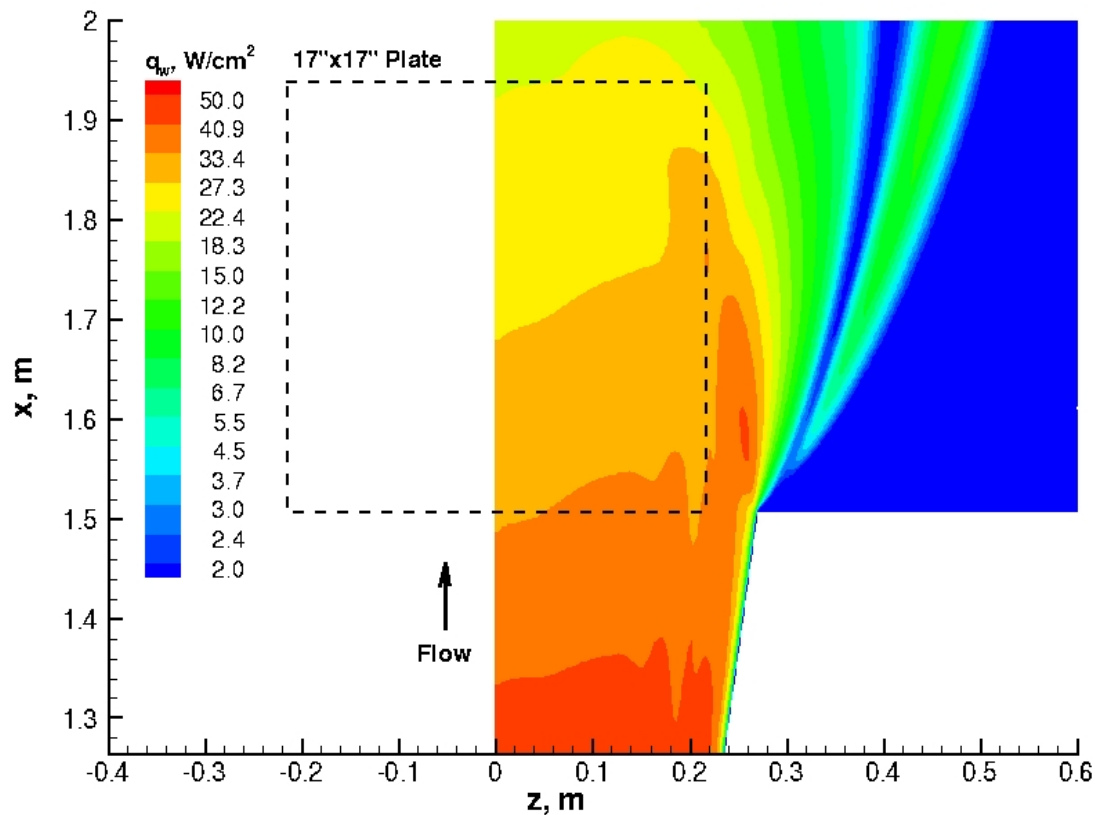
TIHF-2 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 0° plate deflection



- Top view shows surface pressure distribution over a 17"x17" panel test article
- Surface pressure range along the plate centerline: 4.6–2.7 kPa

Computed Surface Heat Flux Contours and Centerline Profiles

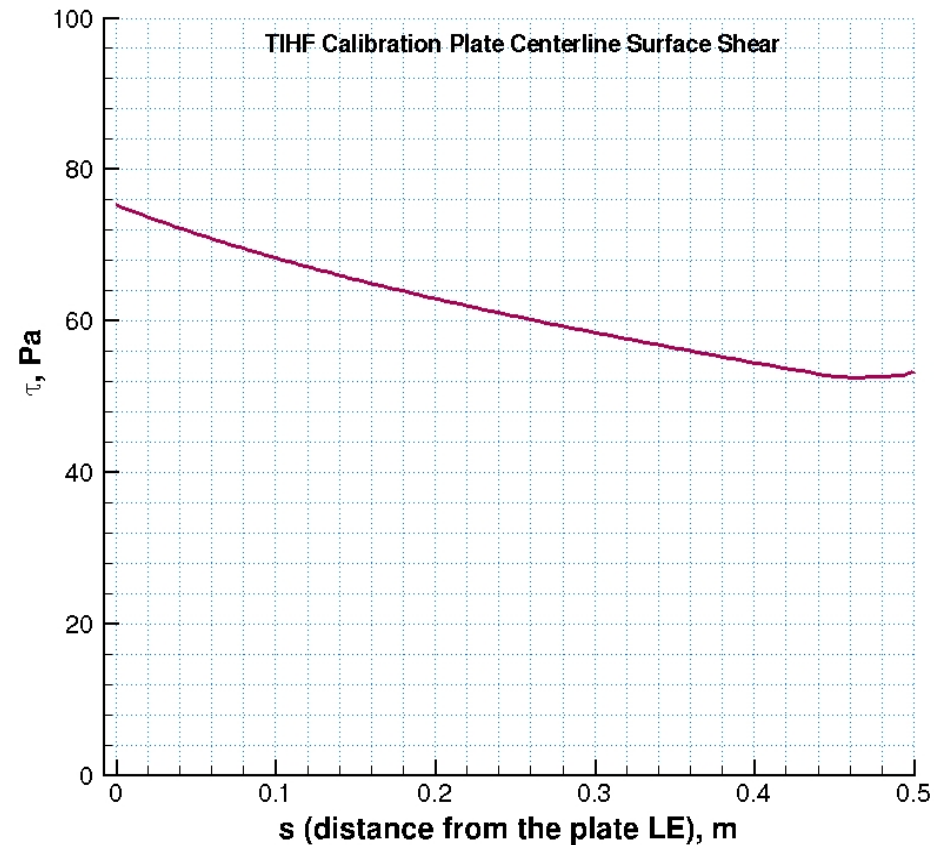
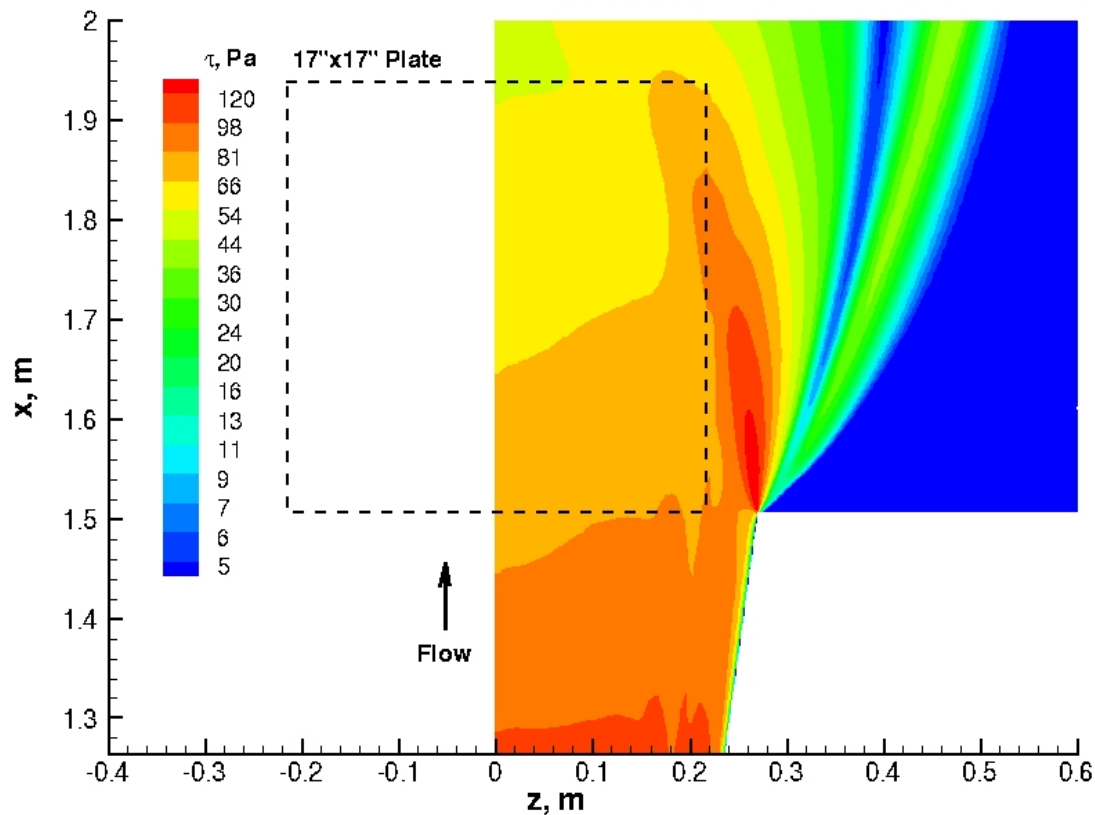
TIHF-2 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 0° plate deflection



- Top view shows surface heat flux distribution over a 17''x17'' panel test article
- CWFC heat flux range along the plate centerline: 33–22 W/cm²

Computed Surface Shear Contours and Centerline Profiles

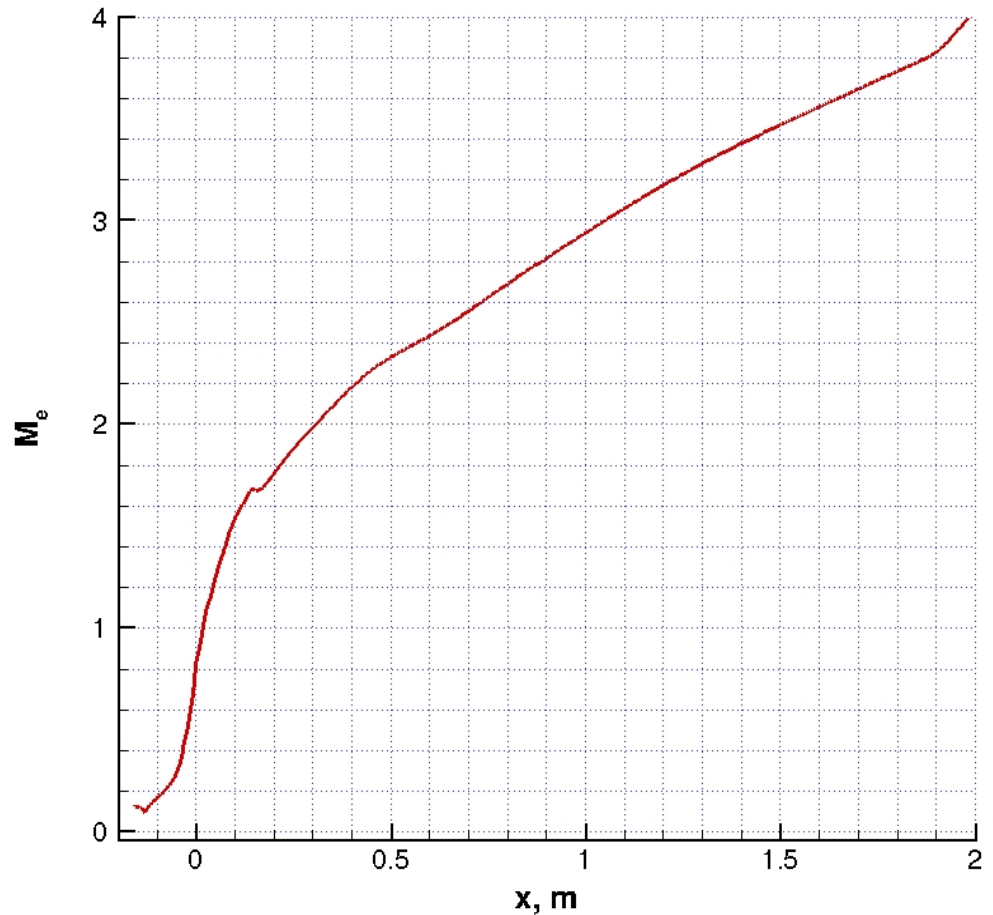
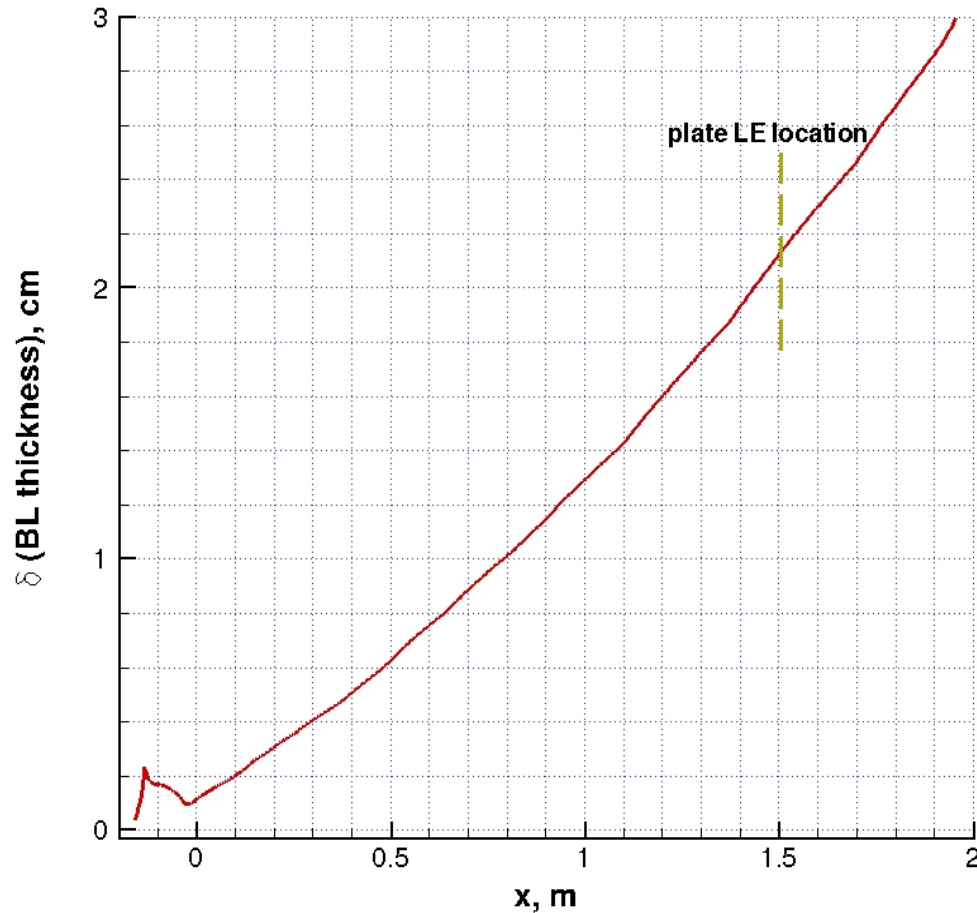
TIHF-2 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 0° plate deflection



- Top view shows surface heat flux distribution over a 17"x17" panel test article
- Surface shear range along the plate centerline: 75–53 Pa

Computed Boundary Layer Thickness and Edge Mach Number

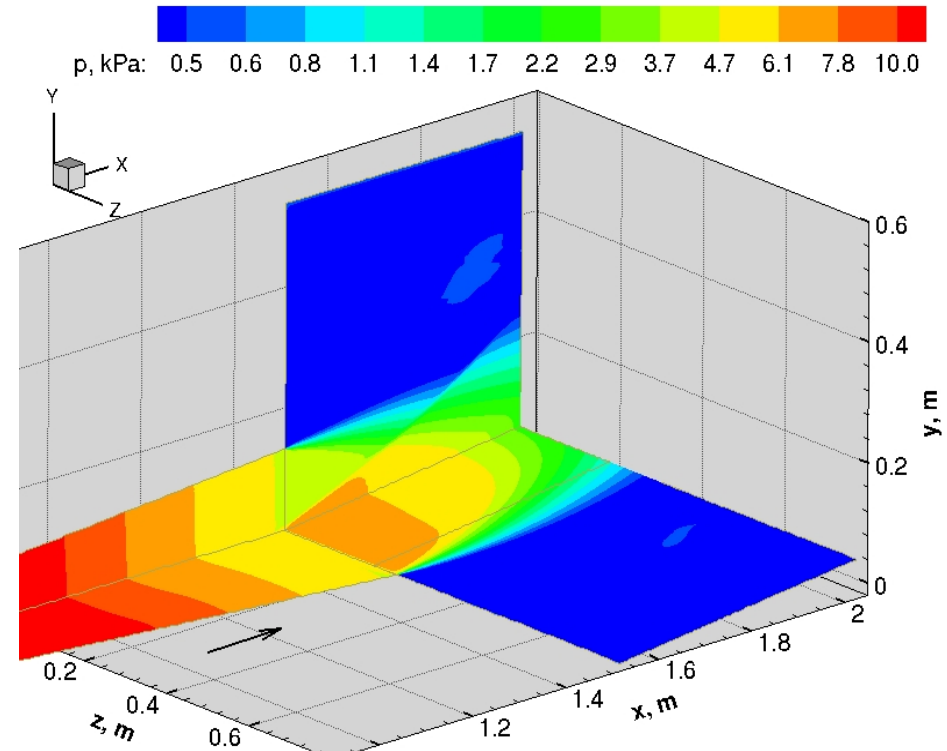
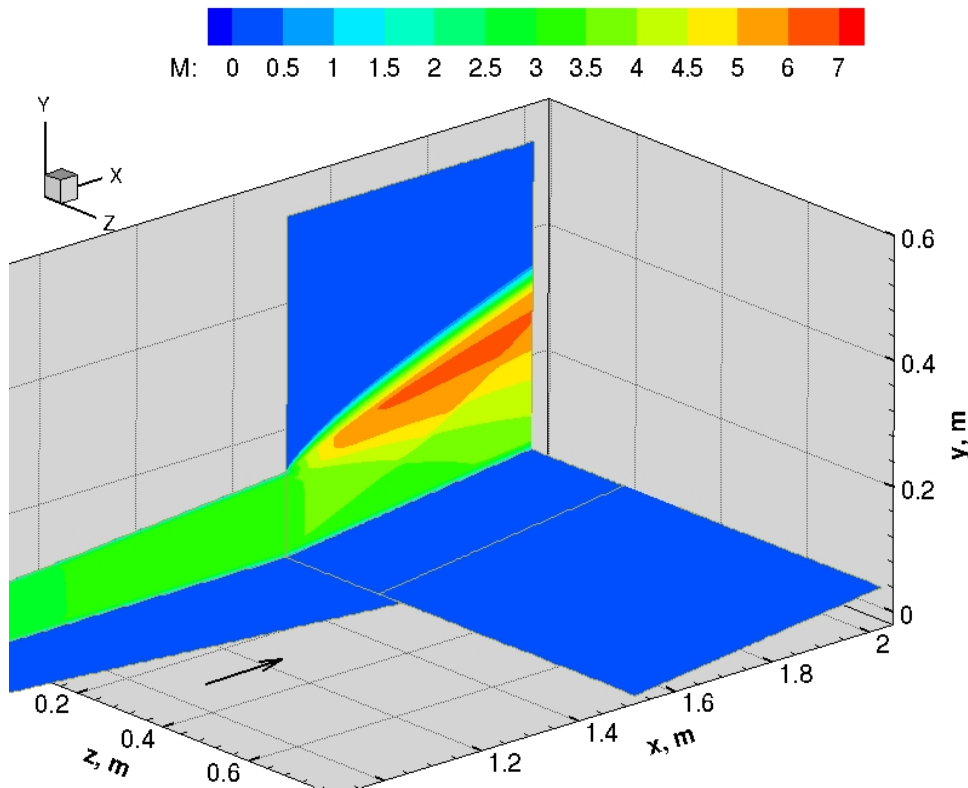
TIHF-2 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 0° plate deflection



- BLE is determined as the location of 99.5% freestream total enthalpy

Computed Flowfield Contours: Expansion Waves and Flow Interaction

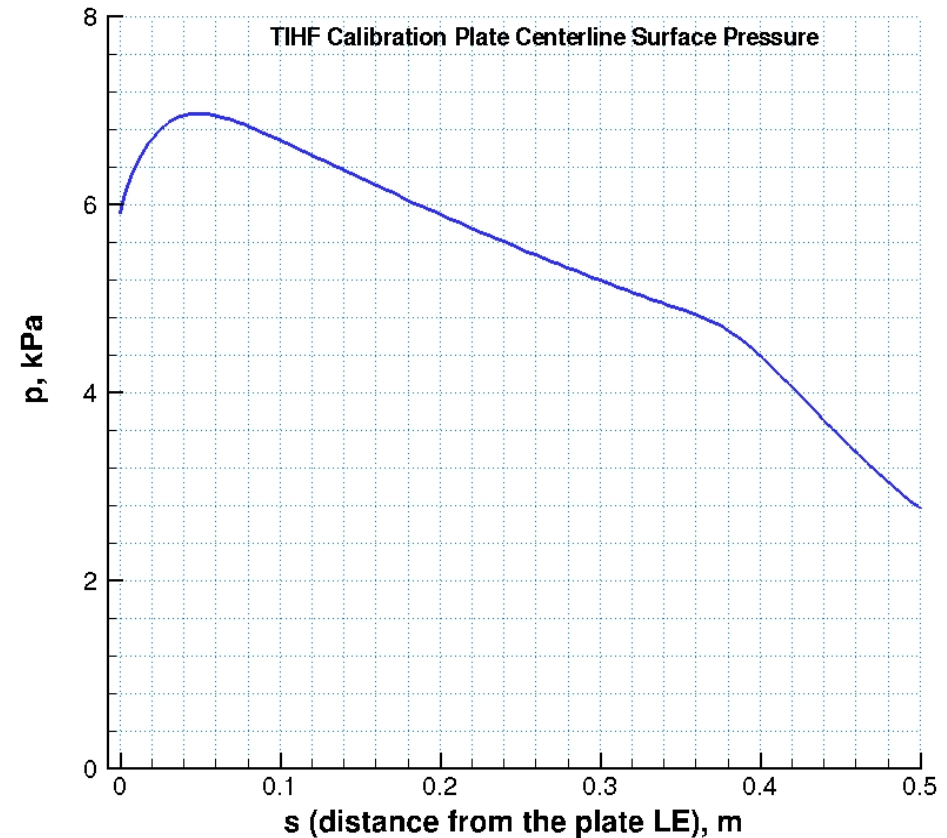
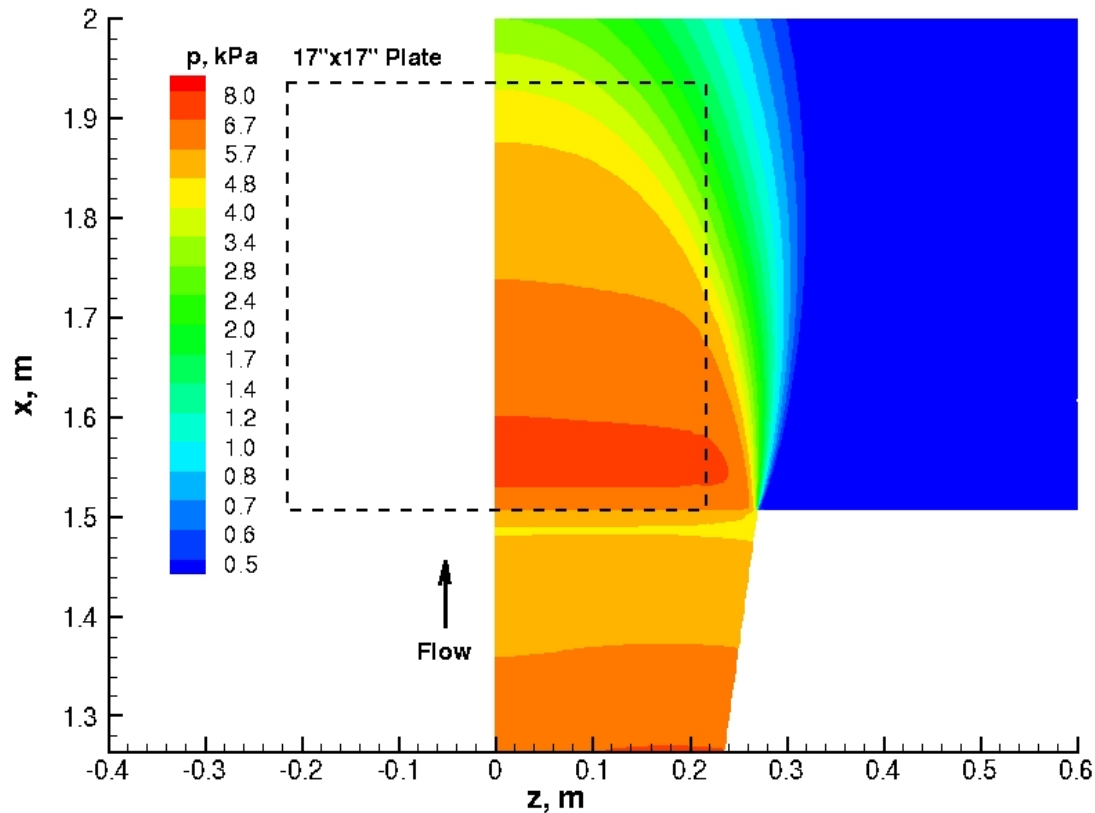
TIHF-2 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 6° plate deflection



- Since the exit Mach number for TIHF-2 is higher than for TIHF-1 (3.47 vs. 2.37), the effect of the expansion wave interaction is felt further downstream from the nozzle exit
- For the same reason, a larger plate deflection angle for TIHF-2 is possible, without seeing adverse effects of the expansion wave flow interaction

Computed Surface Pressure Contours and Centerline Profiles

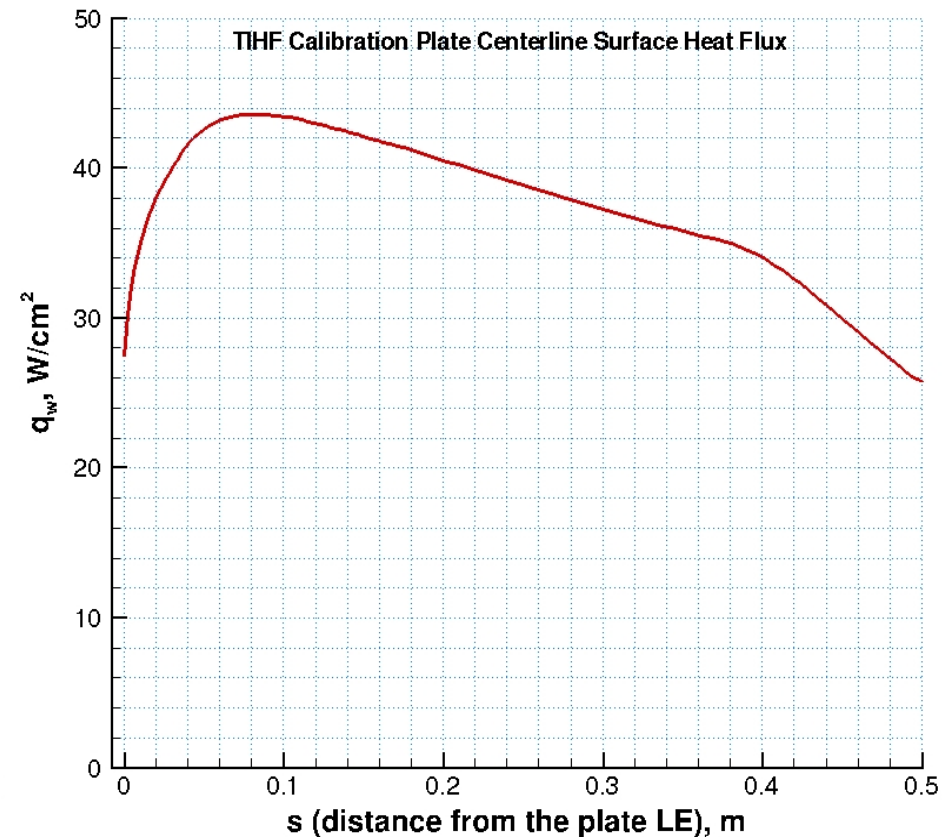
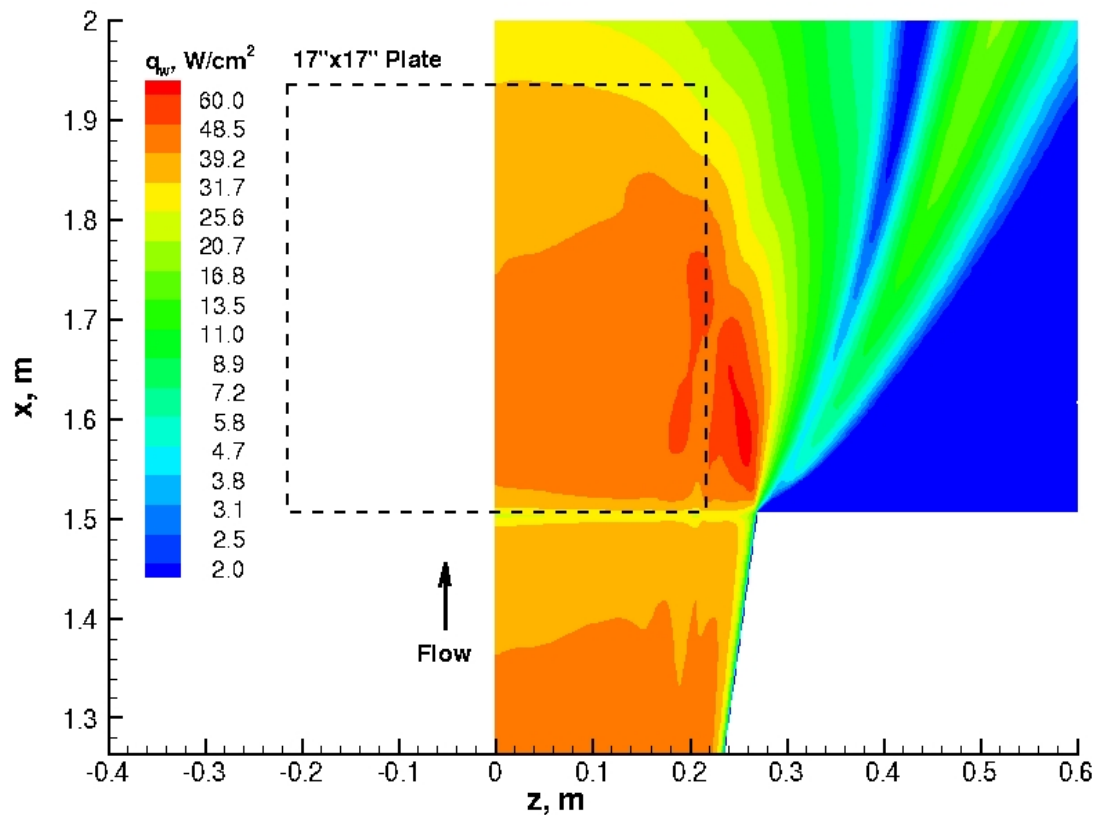
TIHF-2 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 6° plate deflection



- Top view shows surface pressure distribution over a 17"x17" panel test article
- Surface pressure range along the plate centerline: 7.0–4.2 kPa

Computed Surface Heat Flux Contours and Centerline Profiles

TIHF-2 Flow: $p_o = 900$ kPa, $h_o = h_{ob} = 26$ MJ/kg, 5% Ar in air, 6° plate deflection

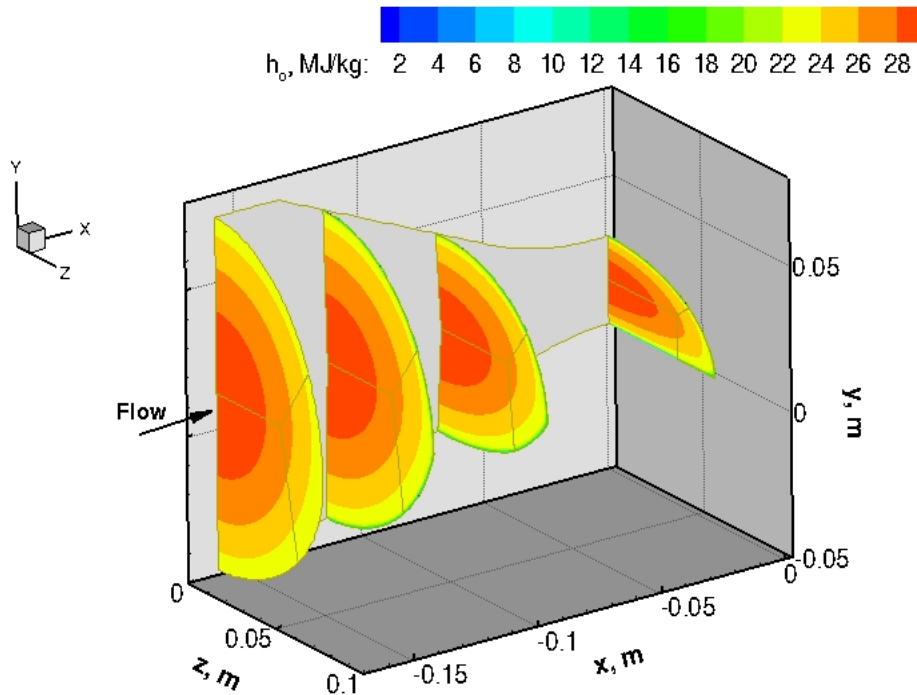


- Top view shows surface heat flux distribution over a 17''x17'' panel test article
- CWFC heat flux range along the plate centerline: 44–33 W/cm²

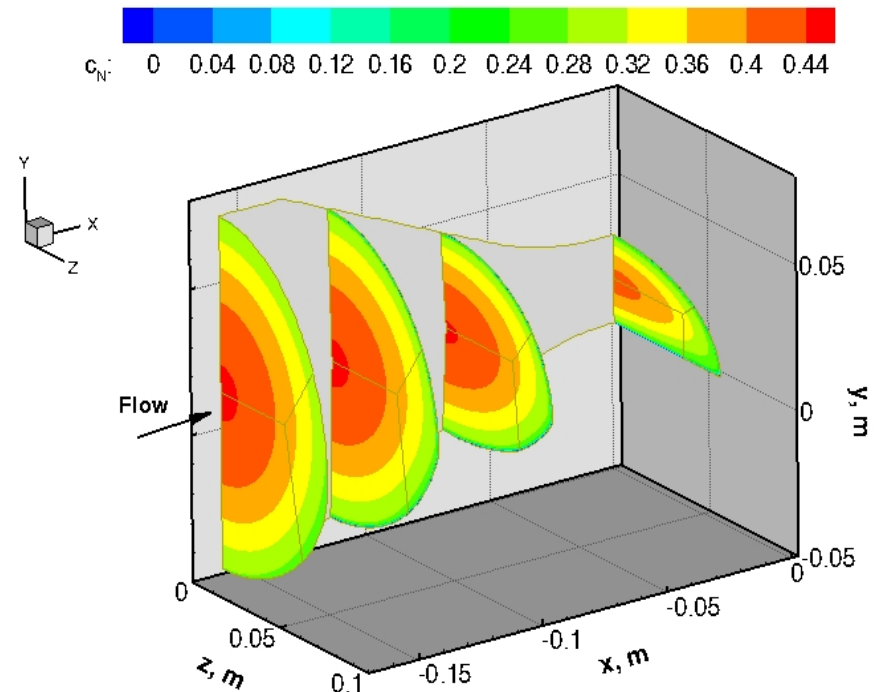
Effects of a Non-Uniform Enthalpy Profile on Predicted Surface Quantities

TIHF-1 and TIHF-2 Nozzle Subsonic Section

$p_o = 900$ kPa, $h_{ob} = 26$ MJ/kg, $h_{ocl} = 29.5$ MJ/kg, 5% Ar in air



Total enthalpy



Atomic nitrogen mass fraction

- Based on the available IHF data using conical nozzles, flow non-uniformity at the maximum facility condition (max current and pressure, without any cold-gas injection at the arc-heater plenum) is expected to be minimal
- Effects of flow non-uniformity on predicted surface quantities are assessed, and the results for TIHF-1 and TIHF-2 are given in the paper

Summary and Concluding Remarks

- Feasibility of the proposed panel test configurations using truncated IHF semi-elliptical nozzles is investigated
- In the semi-free jet test configuration, expansion waves emanating from the corner of the nozzle exit connected to the test box, and their interaction with the incoming flow over the plate, play important roles
 - Mach number at the nozzle exit and plate deflection are the most important parameters in this flow interaction
- The present CFD simulations take into account these effects in order to predict heating levels and distribution over the test articles
 - Maximum recommended plate deflection angles: 4° for TIHF-1 and 6° for TIHF-2
- Computational simulations show that the truncation option 1 can provide a testing capability for test articles as large as 20 cm x 20 cm (8 in x 8 in) while the option 2 should accommodate test articles as large as 43 cm x 43 cm (17 in x 17 in)
- CFD-estimated values of the maximum cold-wall heat flux and surface pressure on panel test articles
 - Option 1: 141 W/cm^2 and 32 kPa, with no plate deflection; 155 W/cm^2 and 39 kPa at 4° plate deflection
 - Option 2: 33 W/cm^2 and 4.6 kPa, with no plate deflection; 44 W/cm^2 and 7 kPa at 6° plate deflection

Acknowledgments

This work was funded by the NASA LEAF-Lite project. The support from the NASA Ames Entry Systems and Technology Division, through contract NNA15BB15C to AMA, Inc., is gratefully acknowledged.